

EXTREMELY LUMINOUS FAR-INFRARED SOURCES (ELFS)*

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ABSTRACT. The Infrared Astronomical Satellite (IRAS) survey uncovered a class of Extremely Luminous Far-Infrared Sources (ELFS), exhibiting luminosities up to and occasionally exceeding $10^{12} L_{\odot}$. We present arguments to show that sources with luminosities $L \geq 3 \times 10^{10} L_{\odot}$ may represent gas-rich galaxies in collision. The more conventional explanation of these sources as sites of extremely active star formation fails to explain the observed low optical luminosities of ELFS as well as their high infrared excess. In contrast, a collisional model heats gas to a temperature of $\sim 10^6$ K where cooling takes place in the extreme ultraviolet. The UV is absorbed by dust and converted into far-infrared radiation (FIR) without generation of appreciable optical luminosity. Gas recombining as it cools generates a Lyman- α photon only once for every two extreme ultraviolet ~ 50 eV photons emitted by the 10^6 K gas. That accounts for the high infrared excess. Finally, our model also is able to explain the observed luminosity distribution of ELFS as well as many other traits.

1. INTRODUCTION TO THE DATA

The most luminous sources identified through the IRAS survey exhibit these properties:

- i) Their FIR luminosities approach and sometimes exceed $10^{12} L_{\odot}$ (Soifer et al. 1986),
- ii) The FIR flux appears uncorrelated with the optical and near infrared luminosity which typically remains around $10^{10} L_{\odot}$ characteristic of fairly normal spirals (Houck et al. 1985, Allen et al. 1985),
- iii) Many ELFS appear to be irregular, disturbed or interacting galaxies (Houck et al. 1985),

* The authors have submitted a more comprehensive article (Harwit et al. 1987) on the same topic to The Astrophysical Journal. Here we only summarize the findings presented in greater detail in that paper.

- iv) The FIR luminosity is directly proportional to the 21-cm radio continuum luminosity (Sanders and Mirabel 1985),
- v) CO observations at 2.6mm indicate a high molecular hydrogen content $\sim 10^{10} M_{\odot}$ (Sanders and Mirabel 1985), and
- vi) The CO lines are abnormally broad, indicating high-velocity motions.
- vii) The infrared excess -- the ratio of FIR to Lyman-line radiation -- is higher by an order of magnitude than in HII complexes (Beck et al. 1986, DePoy et al. 1986).
- viii) Low-ionization states of atoms are more prevalent than the more highly ionized species generally found in HII regions (Allen et al. 1985).
- ix) The luminosity distribution function is roughly proportional to $L^{-5/2}$ for $L \geq 3 \times 10^{10} L_{\odot}$ but declines less steeply below a break in the curve at $\sim 3 \times 10^{10} L_{\odot}$ (Lawrence et al. 1986, Soifer et al. 1986).
- x) Only one extragalactic source in $\sim 10^6$ has FIR luminosity above $\sim 10^{12} L_{\odot}$ (Soifer et al. 1986).
- xi) Intense vibrational H_2 emission characterizes many ELFS (Joseph et al. 1984).

2. MODEL FOR ELFS

We assume that ELFS are the byproduct of collisions among gas-rich galaxies. We picture most of the gas in each of the colliding partners to be concentrated in a central disk, roughly 1 kpc in radius, 0.1 kpc thick and containing $\sim 10^{10} M_{\odot}$ of gas. The indicated pre-collision gas density then is $n_H \sim 10^3 \text{ cm}^{-3}$. Galaxy-galaxy collisions are expected to occur at free infall velocities $\geq 500 \text{ km sec}^{-1}$. The observed CO line widths are consistent with such high velocities and the line strengths suggest the high gas content we have assumed.

If the disks collide face on, the dissipated kinetic energy gives rise to a luminosity $\sim 10^{12} L_{\odot}$ for about $3 \times 10^5 \text{ y}$. More oblique collisions can account for lower luminosities, often with longer enduring interaction. A rough numerical calculation that takes into account a wide range of initial orientations and of center-to-center distances for the colliding pairs gives the luminosity (the dissipation) distribution function shown in Fig. 1. The line drawn through the data points has been arbitrarily anchored to the probability with which the most luminous galaxies are observed. There are no other assumptions aside from the above-listed disk dimensions and mass. The shaded extension of the curve around $10^{11} L_{\odot}$ estimates the contribution of the many glancing (weak) collisions. Collisional activity should not make a pronounced contribution for luminosities well below $3 \times 10^{10} L_{\odot}$, and this appears to account for the break in the luminosity distribution below that luminosity.

Calculation of the luminosity of stars that could form from $10^{10} M_{\odot}$ of gas suggest that a total luminosity of $10^{12} L_{\odot}$ could only be reached with unusually efficient conversion of gas into stars and with an exceptionally high luminosi-

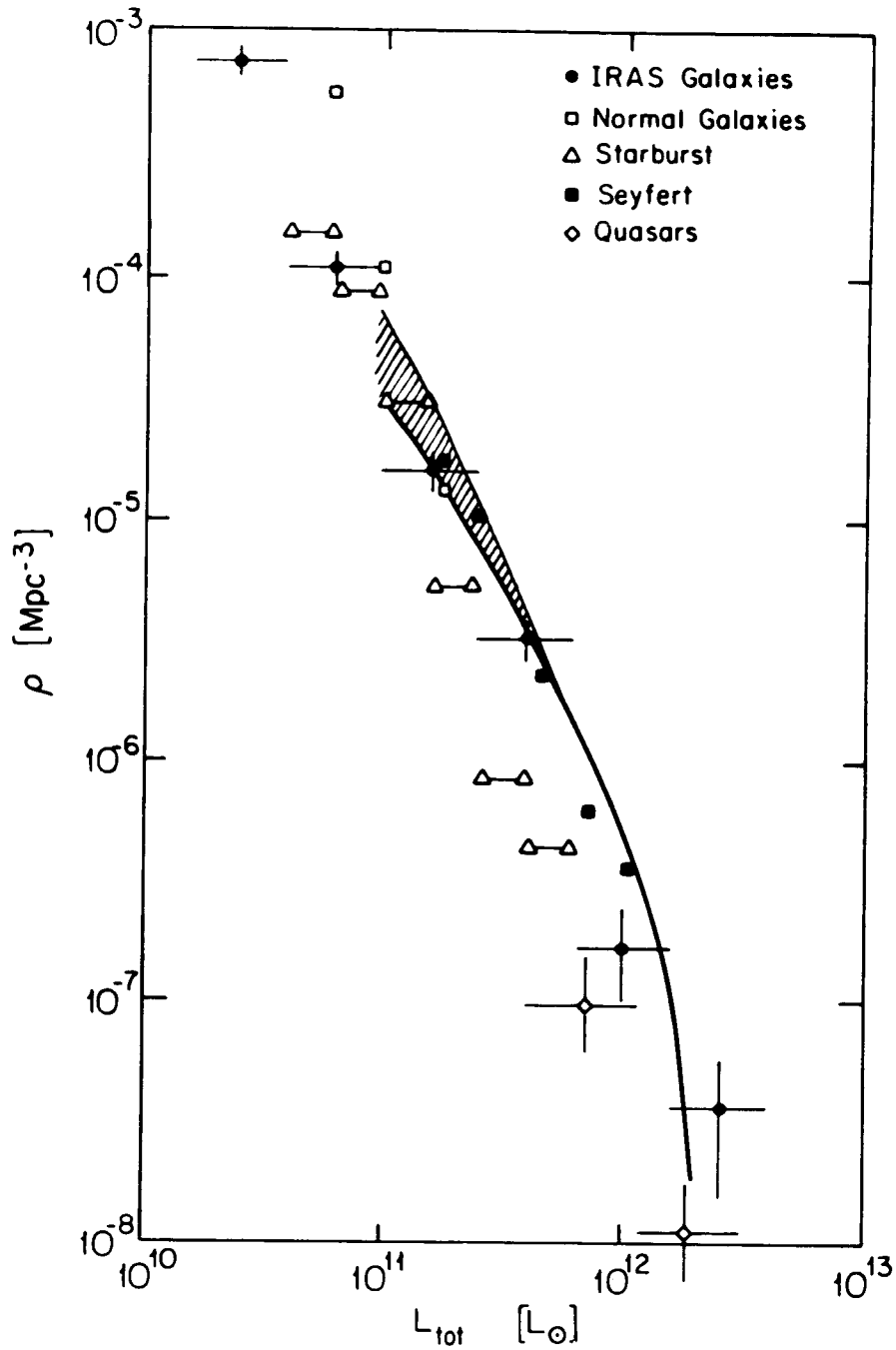


Figure 1 - Data on the luminosity distribution function among luminous FIR sources (Soifer *et al.* 1986) and a calculated fit (solid line and shaded area). A derivation of this fit is presented in a full-length paper by the authors (Harwit *et al.* 1987).

ty to mass ratio for the stars that are formed. Even then, however, we would have to account for the exceptionally low optical luminosity, since it is not clear how one could systematically block all but ~ 1 percent of the optical emission, converting all of that radiation instead into FIR. It would also be difficult to explain the low observed atomic hydrogen line-emission or the radiation from predominantly singly ionized, rather than multiply ionized species. All of these observations break with those traditionally characteristic of HII complexes around massive, luminous stars.

The collisional model does not face these difficulties. Observed gas masses and velocities can account for dissipation rates consistent with the observed luminosities. At collision (Fig. 2) gas temperatures rise to $>10^6$ K. At this temperature the bulk of the energy loss is via cooling through extreme ultraviolet (EUV) radiation. Photons with energies in the 50eV range are emitted. There is little optical flux. Much of the EUV emission is absorbed by grains and converted directly into FIR. Detailed considerations show that only every second EUV photon, on the average, leads to ionization followed by recombination -- to a Lyman- α photon. This accounts for the high infrared excess. The optical line radiation emitted in this layered model (Fig. 3) comes largely from a dusty, partially ionized layer. The partial ionization of the hydrogen accounts for the absence of highly ionized species; those would quickly jump to a lower ionization state by charge exchange with a hydrogen atom. Molecular hydrogen is vibrationally excited in this same partly ionized regime, well upstream of the impact front.

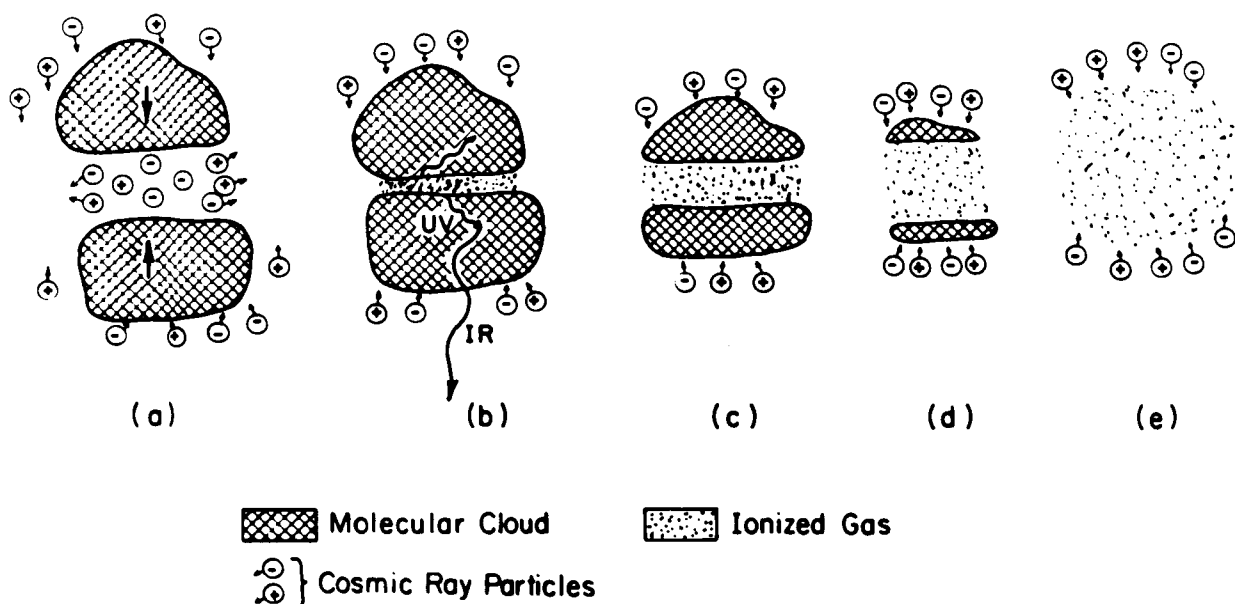


Figure 2 - Schematic Diagram of Colliding Gas Clouds. Two molecular clouds approach. (a) Upon contact, the gas between them is ionized and heated to temperatures above 10^6 K. (b) Ionizing radiation escapes into the molecular gas and produces an ionized layer even before that gas has a chance to collide with the stationary layer of hot gas that has formed. As the collision proceeds, (c,d) the central layer thickens until no more molecular gas remains. Then the hot outer layers of the ionized cloud expand outward to meet trailing, more tenuous halo gas from each of the colliding galaxies (e).

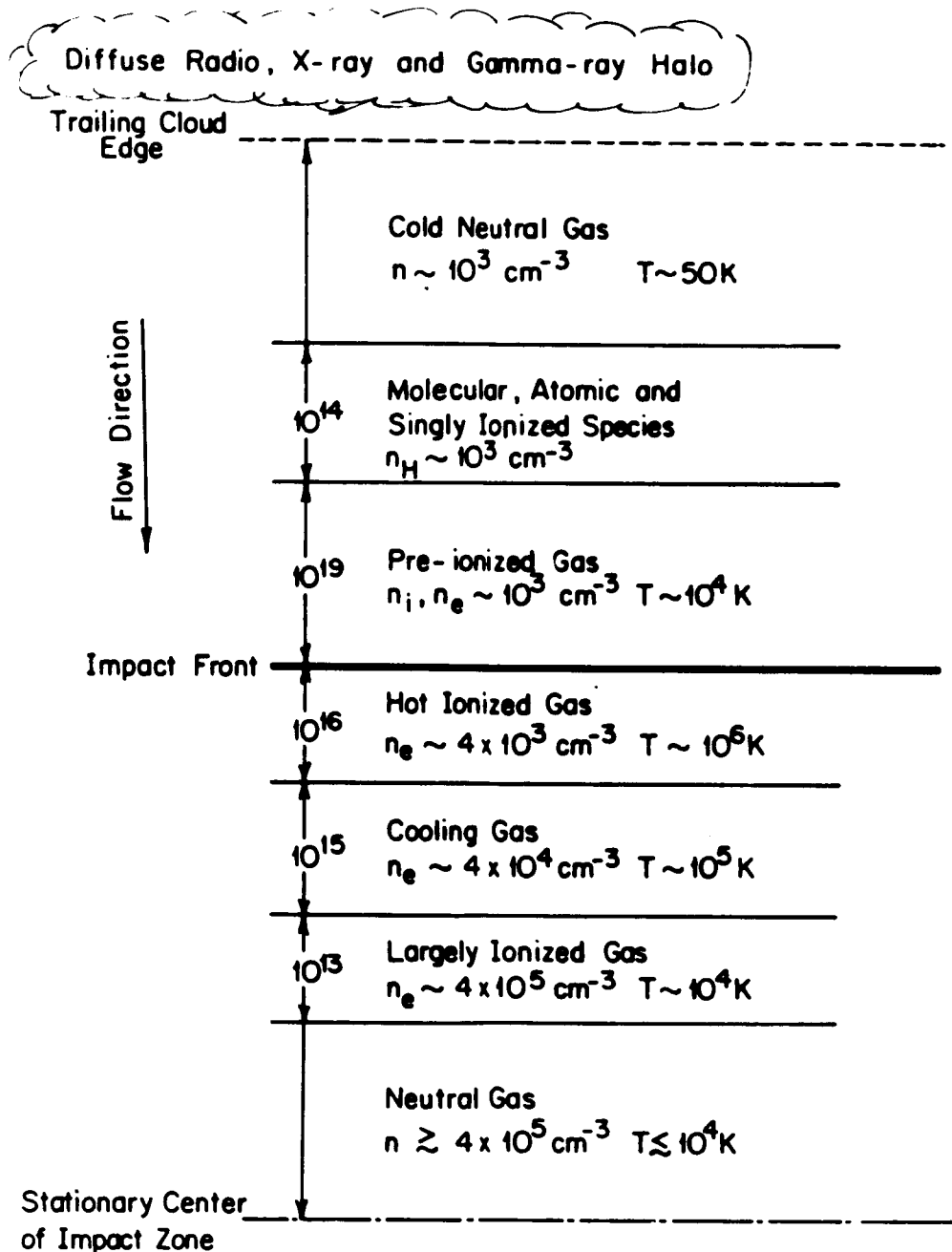


Figure 3 - Layered structure of colliding clouds. At the bottom is the central portion of the colliding disks. At the top the outer pre-collision gas.

More comprehensive arguments also suggest that the cosmic ray acceleration rate and hence the radio flux should be proportional to the gas content of colliding regions, leading to the observed proportionality of FIR to radio continuum emission.

3. PREDICTION

The 10^6 K layer should give rise to highly ionized species such as OIV and

NeV, whose fine-structure emission, respectively at 25.87 and 24.28 μ m, should penetrate through obscuring dust layers, to be observable from Earth. That radiation would not be produced in HII regions and, if observed, would discriminate against starburst models.

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DISCUSSION

BURBIDGE:

First, I would like to remind everyone that more than thirty years ago collisions were thought to be the explanation of radio galaxies. The idea did not last! Second, I want to say that my own view is that the brightest IRAS galaxies are young galaxies forming their first generations of massive ($\sim 100 M_{\odot}$) stars which give both line luminosity and the dust. A few times 10^5 stars are needed, and about 10 generations of them, to make enough dust.

HARWIT:

First, observations tell us that galaxy interaction appears involved. Many of the most extremely luminous sources clearly appear to be interacting partners.

Second, the most luminous phases may last $\sim 3 \times 10^5$ yr, perhaps an order of magnitude less than the lifetime of highly luminous stars. Lower luminosity, more oblique collisions will last an order of magnitude longer. But we are dealing with events of extremely low probability here. Only one galaxy in a million has a luminosity in excess of $10^{12} L_{\odot}$. Quantitatively, our model appears capable of explaining that number of extremely luminous sources.

SCOVILLE:

I don't think the high $L_{\text{IR}}/L_{\text{Br}\alpha}$ line ratio is an insurmountable problem for massive star formation models in interacting galaxies. The HII regions there will have higher dust abundances than standard Galactic HII regions because the cloud-cloud velocities are $\geq 100 \text{ km s}^{-1}$ and fresh grains will be supplied continually to

the ionized gas surrounding the OB stars.

HARWIT:

I would really like to see quantitative estimates of such effects. It appears very difficult to provide a dust absorption shield which will have no holes, and will prevent all but 1% of the optical radiation from escaping. The luminosities involved are so high that dust and gas constituting a shrouding envelope could be blown away by radiation pressure if it did not already have the enormous approach velocities involved in our model.

SHULL:

Your large ratios of infrared to optical flux are predicated on the assumption that the emitting regions are buried deep inside large homogeneous slabs. If you take into account a cloudy interstellar medium, wouldn't much of the optical radiation escape through the 'holes'? Note that much of the cooling will take place in optically thin optical-IR forbidden lines.

HARWIT:

The emitting regions in our model primarily radiate in the far ultraviolet which is readily absorbed by the interstellar gas even if it escapes through holes between clouds. No direct optical radiation is involved. Recombination in tenuous ambient interstellar gas ionized in this way will be extremely slow and result in low luminosity emission from the galaxies' halos.

de JONG:

You have normalized the infrared luminosity function, predicted on the basis of your model, to the observed infrared luminosity function. This implies a certain collision frequency of galaxies at impact parameters of ~ 1 kpc. Have you verified that this implied collision frequency is consistent with that directly derivable from observations?

HARWIT:

Schweizer, in a recent article in Science, estimates that one galaxy in every ten appears to have undergone an interaction in its past. Such figures are still not well established, but they appear sufficiently high, particularly if we recall that many initial encounters may be quite weak - just strong enough to bind two galaxies together in rather eccentric orbits. There may then be several relatively close passes before a substantial collision occurs. In summary, the number of passes two galaxies make past each other could be few times higher than the number of captures that take place.